

SELECTIVE POLYSILICON DEPOSITION FOR FREQUENCY TUNING OF MEMS RESONATORS

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ABSTRACT

A post-fabrication process was developed to tune the frequency of a set of comb-drive resonators by selectively adding polysilicon to their rotors. Selective deposition was performed by electrically heating the resonators in a silane environment using the same input voltage but varying process times. The resonant frequency of individual devices increased 0.7 to 2%, from an average initial resonant frequency of 86.6kHz. A correlation between the change in frequency and the location of the newly deposited material was found and verified in a finite element simulation. The data show the percent change in frequency is also dependent on thermal history and initial material properties. This work describes the trends in a new MEMS resonators frequency tuning method.

INTRODUCTION

High frequency microresonators cannot be readily fabricated to precise specifications because even neighboring devices have submicron variations in size. A post-fabrication process is proposed to tune their resonant frequencies by selectively adding material to their rotors.

This work is the characterization of a new method of frequency tuning of MEMS resonators. It started with the demonstration of selective deposition of polysilicon on fixed-fixed, suspended microbeams [1]. This was done by electrically heating the microstructures in a silane environment, to locally decompose the gas, as shown in the reaction, $\text{SiH}_{4(g)} \Rightarrow \text{Si}_{(s)} + 2\text{H}_{2(g)}$. It was found that the volume deposited was proportional to the predicted temperature gradient along the structures; and the electrical current required to obtain deposition was predicted using an electro-thermal simulation. Subsequently, a test vehicle was designed to show the application of selective polysilicon deposition to frequency tuning [2]. Finite element simulations were performed to design a resonator which could withstand the thermal stresses from the post-fabrication deposition process and to estimate its frequency. The result was the tunable comb-drive resonator (shown in Figure 1). Features of this device include electrically isolated ends of the rotor that allow current to be passed through it; and a single beam suspension which guarantees the location of the hottest spot and thus the deposition on the rotor. In

this paper, a set of these special comb-drive resonators is used in an experiment investigating how frequency is changed by the selective polysilicon deposition trials.

Frequency tuning of microresonators has also been demonstrated by other techniques. One is localized annealing [3], which is similar to the present process in that comb-drive resonators are electrically heated. Wang *et al.* applied the power across the rotor in pulses, and reported a 1-3% increase in resonant frequency. The devices reached temperatures 300-400°C higher than in the present process. Another technique is electronic tuning performed by varying the dc-bias [4]. It differs from the present technique in that it does not produce a permanent change in frequency. Electronic tuning has the advantage that it is active and can be performed on the device in-service. It does, however, introduce noise and parasitic capacitance to the system.

Selective deposition modifies the geometry of the device. An important application of it is in matching the frequencies of two modes of a single resonator to improve its performance, such as in the vibrating gyroscope [5].

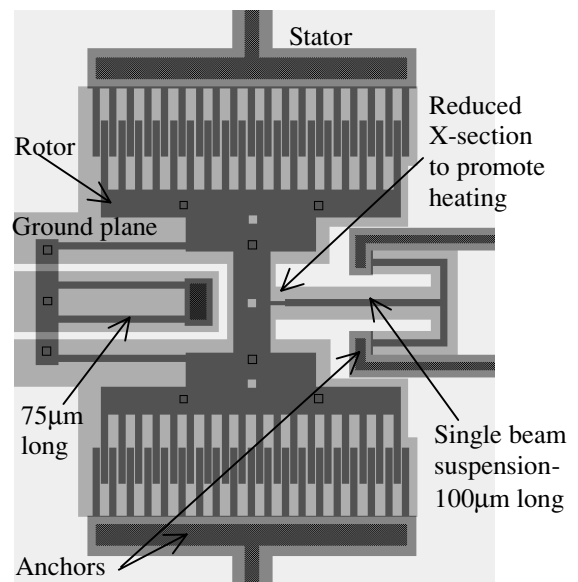


Figure 1 Special comb-drive resonator

EXPERIMENTAL PROCEDURE

Seven samples of the special comb-drive resonator were tested. The comb-drive resonators were fabricated using the MUMPs [6]. They were made of 2 μ m thick, phosphorous-doped polysilicon. The average initial resistance across the rotor was 800 Ω . The devices were released in HF, followed by supercritical CO₂ drying.

The selective deposition of polysilicon was done in a maskless process. A resonator was placed in a chamber filled with silane gas (flowing at 100sccm to a pressure of 150mTorr); 3.5volts were applied across the rotor; and where the local temperature was above 420°C, the gas decomposed, producing polysilicon. Deposition trials of various lengths (1,3,5,10 and 15 minutes) were conducted. The current level was monitored during the trials. The average power dissipation was 10-11mW.

Frequency measurements were made before and after deposition, in air, by applying 20Vpp-ac to the stator and 40V-dc to the rotor and ground plane, and observing the motion of the rotor under an optical microscope. The average initial frequency was 86.6kHz.

RESULTS AND DISCUSSION

Polysilicon was selectively deposited on the single beam of the rotor as shown in Figure 2 for Sample 7. The peak process temperatures were estimated to be 800-900°C using the measured power dissipation and a heat transfer simulation of the devices [7]. The texture of the deposited material is consistent with the estimated peak temperature. Close-ups of the selectively deposited polysilicon are shown in Figures 3 and 4, for Sample 1 and Sample 7, respectively. In Sample 1, deposition is concentrated in a small area. The texture had many pebble-like grains whose volume changed with the temperature gradient on the single beam. In Sample 7, the deposition thickness was uniform (about 0.3 μ m). This

indicates the growth of polysilicon was predominantly in the mass-transfer limited region. The deposition on Sample 1 was consistent with the surface-reaction limited mechanism. The transition point between these regimes is known to be 900°C for silane gas [8], which confirms the temperature calculation made earlier.

The resonant frequency increased in all samples, after the deposition process. When the locations of the selective deposition on the single beams were marked and aligned, the samples with larger hotspots generally showed larger changes in frequency. The comparison is made in Figure 5, using SEM all at 400 times magnification. The lengths of the hotspots varied from 38 μ m for Sample 1 to 73 μ m for Sample 7, on the 100 μ m long single beams. By performing all the deposition trials at constant voltage, the natural variations in properties of the samples caused the variations in thermal response, which produced the hotspots. While the correlation of change in frequency with length is strong, it does not seem to explain every case. Other factors may be the coverage the deposition gives the sample in each case.

The factors governing the length of the hotspots are the power dissipation during processing; the separation of the rotor from the substrate; and the initial thermal and electrical conductivities of the samples, i.e. the local heat transfer in each case. The use of localized annealing alone had also been shown to change resonant frequency [3]. It seems that stiffness was manipulated by introducing residual stress into the devices. This is harder to control and measure than changing stiffness by adding mass.

Frequency is given by $\sqrt{k/m}$; where k is the stiffness of the structure and m is the mass. Mass is increased by the selective deposition process, but the experimental data show stiffness is increased slightly more. The change in frequencies ranged from 0.7 to 2.0%. The finite element analysis below shows that much higher change of frequency is possible from selective deposition on these devices. It shows where deposition will be most effective in increasing the frequency of the resonator.

FEA ON LOCATION OF DEPOSITION

A finite element simulation was developed using Abaqus [9] beam and shell elements to determine the frequency of the special comb-drive resonators for expected changes in the geometry.

Figure 6 shows predictions of the change in frequency when the new film is uniformly 0.3 μ m thick and for variations in the spot size. The spot size is defined in the inset in the Figure 6 by the spot separation and extent of spot on the single beam.

The results show the change in frequency is larger as the hotspot moves closer to the root of the single beam. The amount deposited on Sample 7 would provide nearly 5 times more change in frequency if deposited 10 μ m to the left. The section of the single beam closest to the root was reduced to increase its temperature and promote this result. The elbow in the curves at the spot

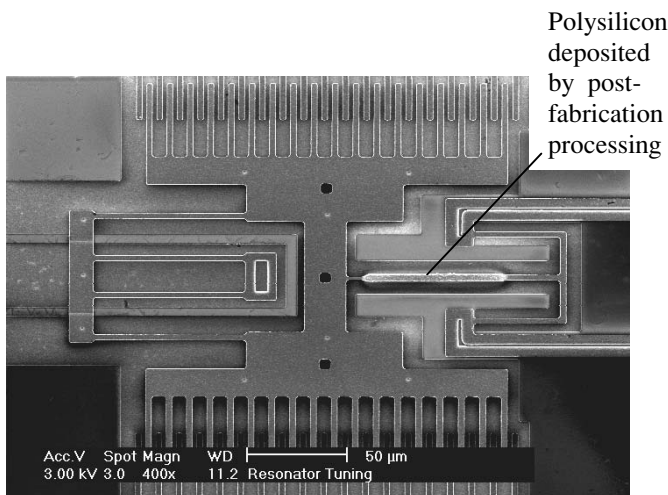


Figure 2 SEM showing selective deposition on Sample 7. The change in frequency was 1.96%.

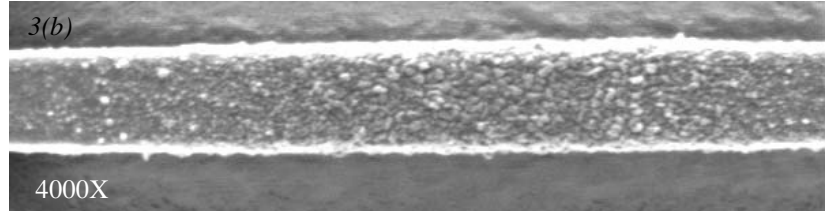
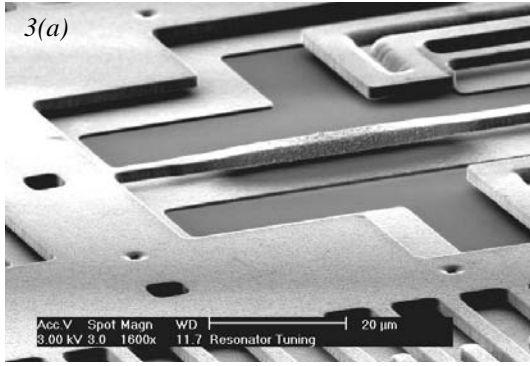


Figure 3(a-b) Close-up views of selectively deposited polysilicon on Sample 1.

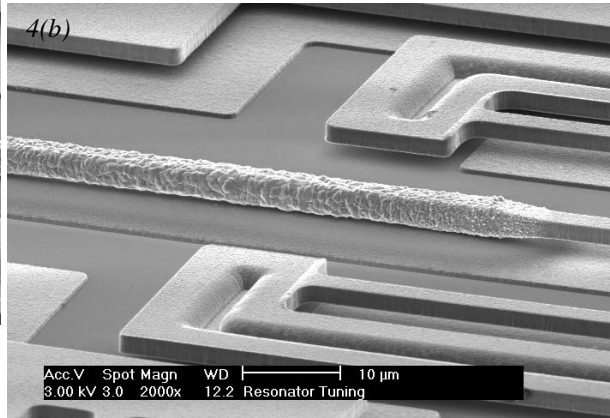
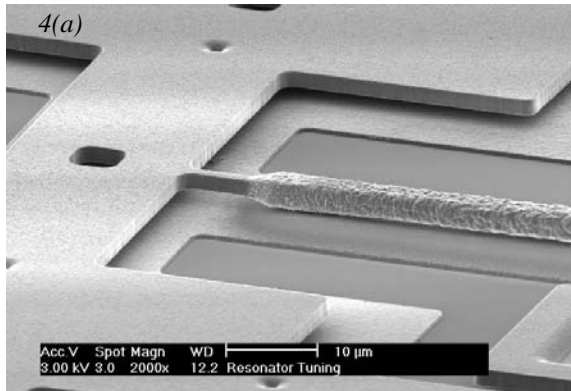


Figure 4 (a-b) Close-up views of selectively deposited polysilicon on Sample 7.

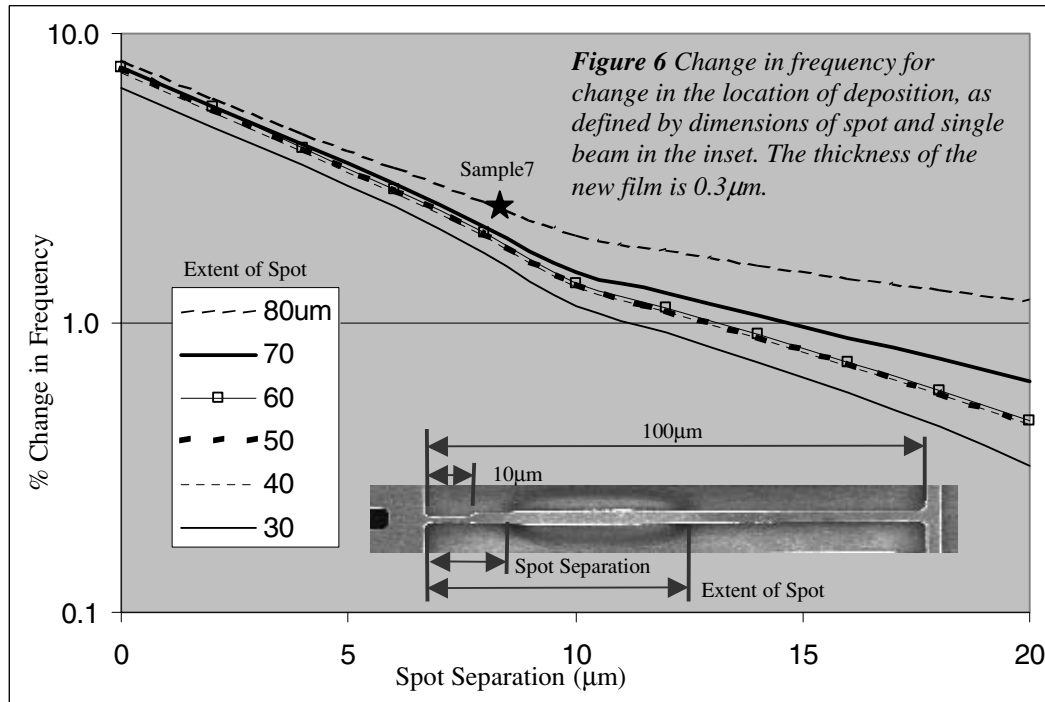
Sample #		Δf
1		0.7%
2		0.7%
3		1.4%
4		1.5%
5		0.8%
6		2.0%
7		1.96%

Figure 5 A correlation was found between the length of the hotspot and the change in frequency. SEM are all at 400X.

separation of 10µm occurs because the effect on stiffness is greater when material is added in the reduced cross-section.

The results also show the change in frequency increases as the extent of the hotspot increases, but the relationship is not linear. Variations in the extent of spot from 40 to 60µm, have almost the same effect on frequency. The curve for the extent of spot of 80µm is much higher than the rest because the effect of stiffness increases as the new deposition approaches the other end of the single beam.

The new film thickness assumed in the simulation was a good approximation of the results for Sample 7. The spot separation and extent of spot for sample 7 was 8µm and 80µm, respectively, as shown by the star in Figure 6. The change in frequency calculated at those conditions was 2.2%, which is in good agreement with the measured value for Sample 7.



CONCLUSIONS AND EXTENSIONS

The factors governing frequency change from selective polysilicon deposition on a resonator include the location of the new material, the process temperature, and initial material properties. Adding mass to the resonator changes frequency by increasing stiffness and weight. It was shown that the new material should be positioned as close to the root of the single beam as possible in the special comb-drive resonator to obtain a large change in the k/m ratio.

The following extensions of this work are suggested [7]. To better define the location of deposition, the heat transfer analysis should become the priority of the design. To control the texture of the deposited polysilicon, a power regulating feedback circuit should be designed and built. To obtain precise frequencies, *in situ* measurements should be made during the deposition trials.

ACKNOWLEDGMENTS

This research was funded by the University of Michigan Rackham Merit Fellowship and Research Grant # F30602-98-2-0227 from DARPA. The authors wish to thank Professor Richard A. Scott of the University of Michigan for advice on conducting the research and the finite element simulations.

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